

# Space Weather at 75 AU

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**Abstract.** Recent outer-heliosphere observations are reviewed from a space weather point of view by comparing the nature of solar wind, solar particle, and cosmic ray variations at the Voyagers and 1 AU. While the Sun still controls the interplanetary medium at 75 AU, the nearby boundaries of the heliosphere exert a strong influence on the environment.

## INTRODUCTION

The agents of space weather at 1 AU, including transients such as coronal mass ejections (CMEs) and shocks, variations in the interplanetary magnetic field, solar and interplanetary particle events, and solar UV and x-rays, all make their connection to 1 AU across a distance of “only” 150 million km, allowing them to act on time scales ranging from 8 minutes to a few days. As a result, it is usually possible to make a direct connection between events observed on the Sun (be it a CME, flare, or passage of an active region or coronal hole) and subsequent effects on the near-Earth environment. In the outer solar system, say beyond 30 AU, the time scales are slowed by a factor of  $>30$ , and the intensities of solar wind and solar particles are diminished by a factor of  $>1000$ . As we will see, this change in distance scale has a rather dramatic effect on the manner by which the Sun exerts its control on the interplanetary environment, and on the nature and magnitude of variations in that environment.

In order to encourage an interest in space weather in the outer heliosphere, the reader is invited to imagine that he/she resides on a Kuiper Belt Object (KBO) orbiting at  $\sim 75$  AU. Imagine that this society launched two Voyagers in the 1950's as part of their space program, using a gravity assist at Jupiter in 1979 to reach Saturn, Neptune, and Uranus, and to carry on towards the boundaries of the heliosphere. This KBO society also recently positioned two spacecraft (SOHO and ACE) at L1 in order to monitor the Sun and understand how it affects the outer heliosphere.

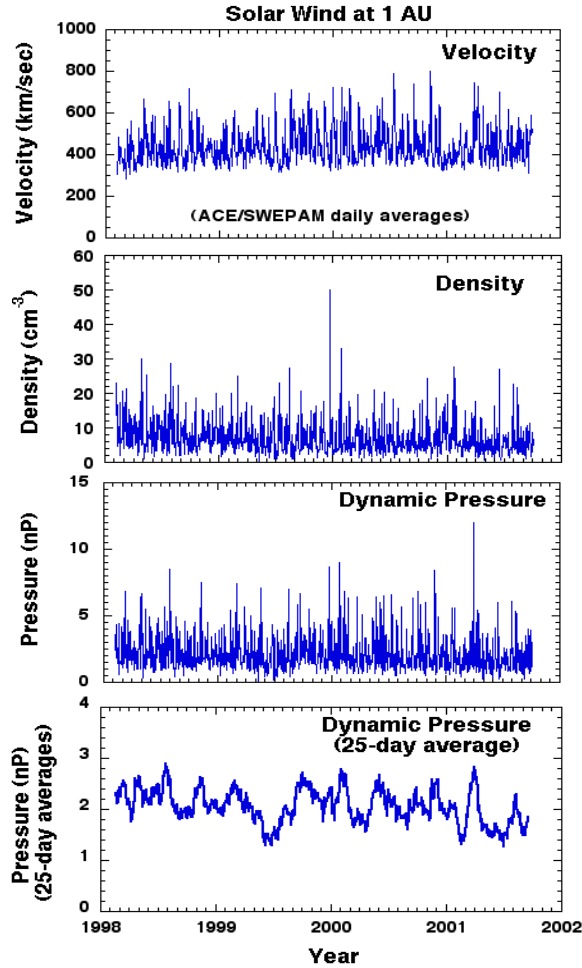
This paper will survey outer-heliosphere observations from a space-weather point of view. It will compare the nature of solar-wind transients at 1

AU and beyond 50 AU, follow solar energetic particles on their six-month journey from the Sun to 70 AU, look at the nature of cosmic-ray intensity variations in the inner and outer heliosphere, assess the nature of life near the termination shock in a high-radiation zone, and compare particle intensities near and far from the Sun.

## SOLAR WIND TRANSIENTS

The five-year period from 1998 through 2002, including the maximum of solar cycle 23, has provided the best opportunity yet to observe and understand the effects of solar variations on the near-Earth environment because of the array of new spacecraft and instruments now in operation. Similarly, Voyager now has a first opportunity to explore the effects of solar maximum beyond 60 AU from the Sun. During 1998 thru 2001 there were  $\sim 4000$  CMEs observed by SOHO [1], about 5% of which could be identified as interplanetary CMEs (ICMEs) observable at Earth [2]. In addition, ACE observed  $\sim 200$  interplanetary shocks at L1 during this period [3].

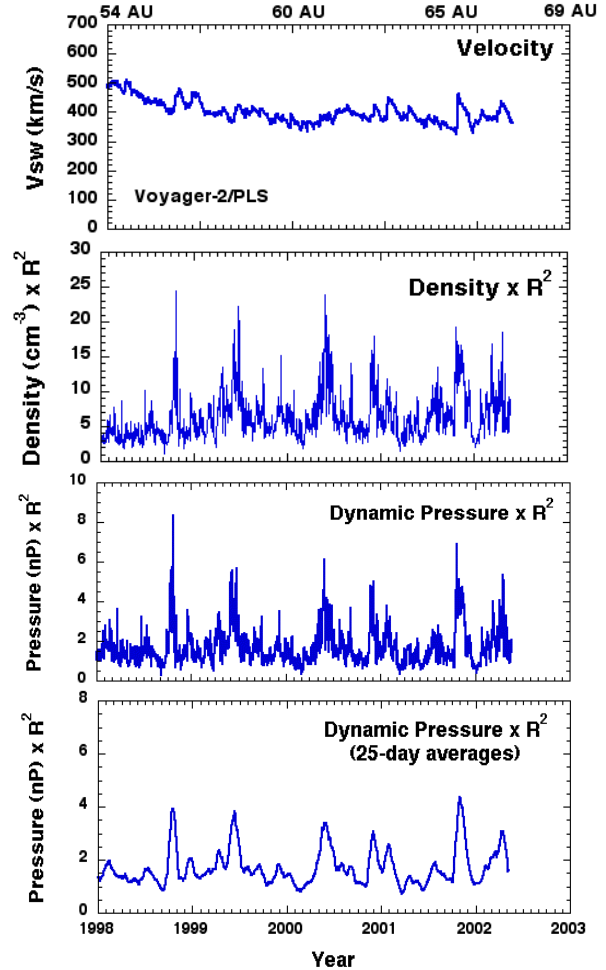
Daily average solar-wind parameters at 1 AU during this time period (top three panels of Figure 1) reveal considerable high-frequency time structure, much of it associated with CMEs. Contrast this with Voyager-2 observations during the same period (Figure 2), where the solar wind speed rarely varies by  $>10\%$  from one day to the next, where the hundreds of individual ICMEs observed at Earth no longer stand out, and where the dominant solar wind structures are merged interaction regions (MIRs) that occur only infrequently but last for weeks at a time (see, e.g., [4]).



**FIGURE 1.** Daily average (top 3 panels) and 25-day average solar wind data at 1 AU from ACE/SWEPAM.

Merged interaction regions (MIRs) result from the entrainment of slower wind by faster, upstream wind (e.g., [5]). During solar maximum the highest velocity solar-wind structures are associated with ICMEs, and the fastest and largest ICMEs eventually become the core of MIRs in the outer heliosphere. In contrast to the many ICMEs and shocks observed at 1 AU, only ~6 MIRs and ~18 shocks were observed by Voyager 2 from 1998 through mid-2002 (J. Richardson, private communication; see Figure 2). From January 1998 to June 2002 Voyager-1 moved from ~69 to ~85 AU at an average heliographic latitude of +33.6°, while Voyager-2 moved from ~54 to ~62 AU at an average latitude of -21°.

From daily-average data at 1 AU (top three panels of Figure 1) it is difficult to recognize the structure that will emerge at Voyager-2. However, with 25-day running averages (bottom of Figure 1) it is evident that 1-AU solar wind does include time structure similar to that observed in the outer heliosphere.



**FIGURE 2.** Daily average and 25-day average solar-wind data from the PLS instrument on Voyager-2.

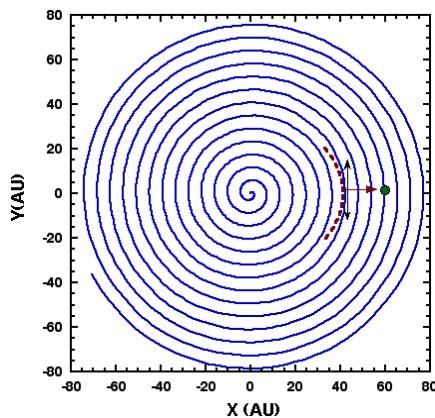
### Bastille-Day Event in the Outer Heliosphere

The solar fireworks of July 14, 2000 (Bastille Day event) led to the largest space weather events at Earth of this solar maximum. News of the Bastille Day event did not reach Voyager-2 until 6 months later, when an interplanetary shock was observed [6], followed by a Forbush decrease in the cosmic-ray intensity and an increase in the low energy particle intensities that reached a maximum about a month later [7, 8]. Although the arrival of the Bastille Day shock is more difficult to identify at Voyager-1 because the plasma instrument is no longer working, there is a Forbush decrease in the cosmic ray intensity starting in early February, 2001 that is comparable to that at Voyager-2, followed by an increase in the ~1 MeV particle intensity peaking at ~5/1/01.

# SOLAR ENERGETIC PARTICLES

## The Great Race

In the Bastille-Day event the intensity of  $\sim 1$  MeV protons at Voyager-2 peaks well after the arrival of the shock. This is common in the outer heliosphere [9], while in the inner heliosphere low-energy shock-accelerated particles typically peak at the shock. However, there are also instances in the outer heliosphere where most of the particles arrive before the shock, as in 1998 [7]. Simulations by Rice et al. [9] show that particles can arrive late if the shock has weakened and can no longer inject and accelerate particles by the time it reaches Voyager-2.



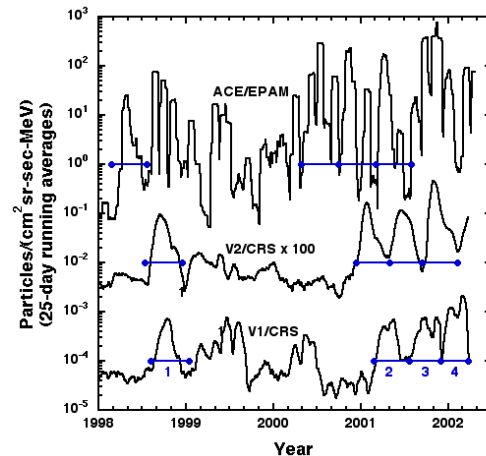
**FIGURE 3.** The nominal IMF is shown out to 80 AU, including a shock assumed incapable of injecting particles beyond 40 AU and a spacecraft at 60 AU.

The illustration in Figure 3 assumes that the shock stops accelerating particles at 40 AU. Particles observed at 60 AU will have been transported from inside 40 AU to 60 AU by a combination of diffusion and convection. Indeed, particles inevitably move by both processes, but it is not obvious which approach is best to win the race from the last point of acceleration to the spacecraft. In the inner heliosphere 1-MeV particles generally diffuse in radius considerably faster than they are convected. In the outer heliosphere diffusion is much more difficult for low-energy particles because the magnetic field lines are so much longer (the length of the Parker spiral from 0 to  $R$  AU is  $\sim R^2/2$  for a nominal solar wind speed of  $\sim 400$  km/sec). Particles that move primarily by convection arrive late because the shock speed exceeds the convective speed. Particles that move primarily by diffusion may arrive either early or late, depending on whether they can advance faster by moving along the Parker spiral faster than by convection [7]. It is also possible that particles can advance more quickly by

diffusing across field lines (much like Rosie Ruiz “won” the 1980 Boston marathon by running the first few km, leaving the course and taking a subway across town, and then rejoining the race just before the finish). Decker et al. [10] have performed simulations of particle events such as this and compared them with the observed time intensity profiles and anisotropies.

## Solar Particle Intensities in the Outer Heliosphere

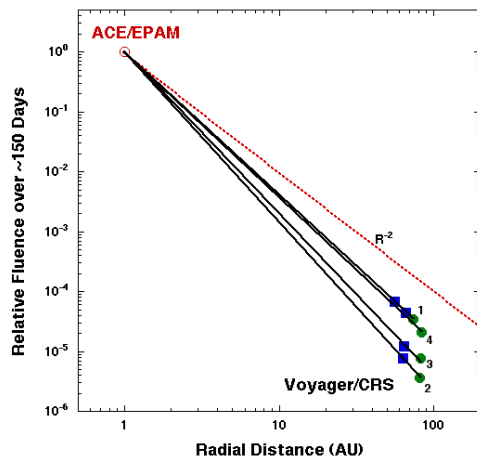
Because of the difficulty of tracing individual SEP events from 1 AU into the outer heliosphere it is instructive to take a more global view. Figure 4 shows 25-day running averages of the  $\sim 2$  MeV particle intensities from ACE and the two Voyagers. Note that at the Voyagers there are only a few, very broad intensity maxima. While these are difficult to match with 1-AU events using daily-average data, there is more hope with 25-day averages. The brackets labeled 1 to 4 in Figure 4 represent an attempt to relate particles that originated in the same series of events at the Sun, taking into account propagation delays. The first of these includes the events of April/March 1998, the second is centered on the Bastille Day event, the third includes the events of Nov. 2000, and the fourth the events in April 2001. A fifth period visible in late 2001 at 1 AU is just starting to appear at Voyager-2.



**FIGURE 4.** Intensity of SEP protons at 1-AU (1.2–5 MeV) and the two Voyagers (1.8–3.3 MeV). Intervals during which the intensities were compared are indicated (see Figure 5).

Integrated particle fluences from four selected periods (see Figure 4) are plotted versus radial distance in Figure 5. In all cases particle intensities in the outer heliosphere are smaller than would be expected from simple scaling by  $r^{-2}$ ; with suggested slopes ranging from  $r^{-2.4}$  to  $r^{-2.8}$ . Intensities at the two Voyagers appear to be consistent with the same radial

dependence in spite of the  $>50^\circ$  latitude separation. Decker et al. [13] obtained similar results for protons accelerated in co-rotating interaction regions (CIRs).



**FIGURE 5.** Measured fluence of  $\sim 2$  MeV protons at ACE, Voyager-1, and Voyager-2 for the periods in Figure 4.

There are several factors that affect how SEP intensities vary with distance from the Sun. The most important of these is probably adiabatic energy loss, coupled with a typically falling SEP energy spectrum ( $dI/dE \sim E^b$  with  $b \approx -4$  to  $-2$ ). Solar particle events generally originate at low heliographic latitudes ( $<30^\circ$ ). If particles escape to higher latitudes by cross-field diffusion the low-latitude intensities will decrease faster than  $r^{-2}$ .

Other factors work in the opposite direction. Although the Voyagers are connected to the near-Sun region at all heliographic longitudes over a 25-day period, and thus integrate over all SEP events that occur during these 150-day periods, observations at L1 are well connected to only  $\sim 120^\circ$  of solar longitude at a time – particles accelerated on the back side of the Sun (viewed from Earth) tend to escape into the outer heliosphere before they can be observed at L1. An  $r^{-2}$  radial profile might be expected if the vast majority of the particles originate inside 1 AU, as appears to generally be the case at higher energies ( $>10$  MeV/nucleon). Continued acceleration beyond 1 AU will tend to flatten the radial dependence. It is clear that the interpretation of SEP intensities in the outer heliosphere is a very interesting problem that could benefit from theoretical modeling and simulations taking into account all relevant processes.

### 150-day Periodicities in the Outer Heliosphere

The Voyager data in Figure 4 appear to have a periodicity of  $\sim 150$  days during 2000-2002. In addition, the same time structure is seen (shifted in time) in  $\sim 150$ -day averages of the frequency of

interplanetary shocks observed by ACE (not shown here for lack of space). It is well known that a variety of solar phenomena exhibit  $\sim 150$  day periodicities, including x-ray flares, SEP events, and the solar wind (see. e.g., [12]). Other periodicities have also been reported (e.g., [13, 14]). Hill et al. [15] reported periodicities of  $\sim 150$  days in the outer-heliosphere ACR intensity during 1998-1999. Evidence that MIRs act as barriers to produce snow-plow-like increases in the intensity of ACRs in the outer heliosphere [7, 16] provides a mechanism for coupling the time structure of MIRs (Figure 2) to that of ACRs. It is beyond the scope of this paper to investigate whether the interplanetary periodicities apparent in 2000-2002 are statistically significant, as in Hill et al. [15]. However, it appears that the interplanetary medium introduces a low-pass filter into the very chaotic, high-frequency activity that characterizes solar maximum near the Sun. As a result, the outer heliosphere may be a preferred location to investigate this mysterious rhythm of solar activity.

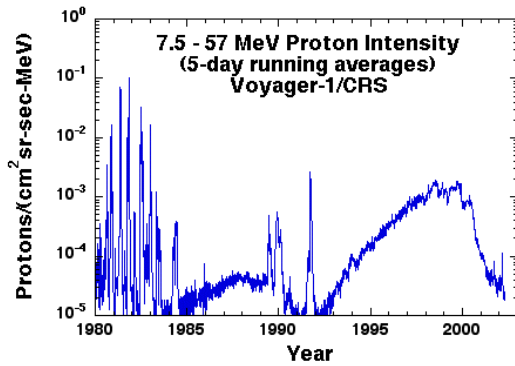
### High-Energy SEPs in the Outer Heliosphere.

Although it is desirable to extend the analysis in Figure 7 to higher energies, this proves to be difficult, as illustrated by the time history of 7.5 - 57 MeV protons observed by Voyager-1 (Figure 6). Particle intensities in the early 1980's were dominated by the SEP events of solar cycle 21. However, by the next solar maximum, with Voyager-1 at  $\sim 40$  AU, only a few SEP events are evident, including the well-known March 1991 event. From 1995 to 2000 it very difficult to observe SEP events at Voyager-1 in this energy range because of a steady “background” that emerges in 1992 and remains through 2000. This background, due to ACR hydrogen, increases in intensity as the Voyagers approach the termination shock and is also subject to diminishing solar modulation effects. Anomalous H is also evident during the 1987 solar minimum at much lower intensity (Fig. 6). Stone [17] reviews estimates of the termination shock location based on approaches that include extrapolating the ACR gradients [18].

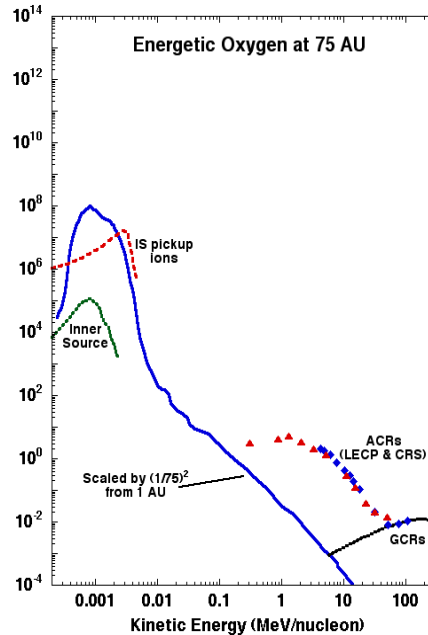
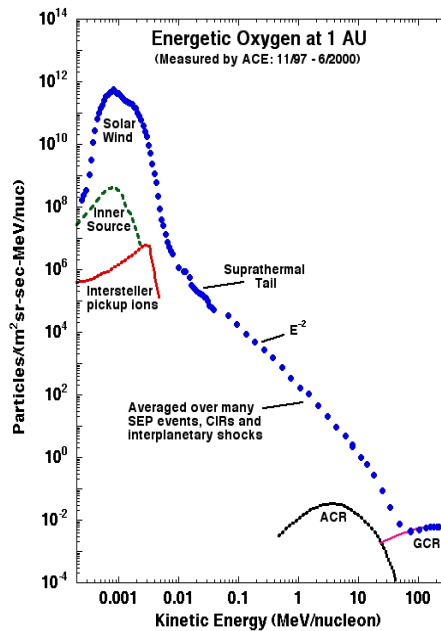
Measured and calculated solar-minimum spectra for cosmic-ray protons are shown in Figure 7, where ACR H is the dominant proton component from  $\sim 5$  to  $\sim 140$  MeV at Voyager-1. The theoretical curves are from a model by Cummings, Stone and Steenberg (here-in-after CS&S) that was fit to ACR species at Voyager-1&2 [19]. Also shown is the deduced ACR H spectrum at the termination shock for a relatively weak shock (compression ratio = 2.4).

It is reasonable to ask whether ACR intensities at the termination shock will constitute a radiation hazard for the Voyagers. The proton spectrum that CS&S

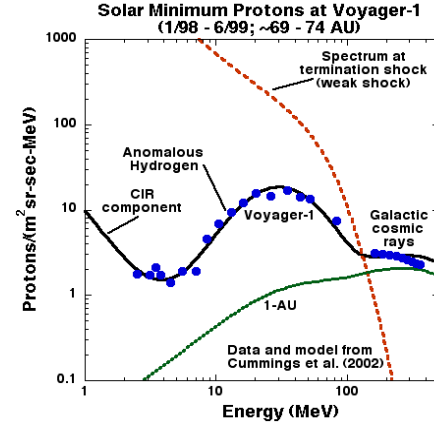
deduce for the termination shock (Fig. 7) is very similar in shape and intensity to that observed near Earth during the peak of the Bastille Day event [20] – the largest SEP event observed at Earth since 1989 – if the Bastille-Day spectrum (averaged over 8-hours of maximum intensity) is divided by  $10^4$ . In contrast, the Voyagers may experience maximum particle intensities near the termination shock for a few years, leading to a total fluence somewhat less than that of the Bastille Day event at 1 AU. So, while the termination-shock radiation level (if experienced at Earth) would exceed NOAA SEP alert levels for several years (in the case of a weak shock), it will probably not present a hazard to the Voyagers. For a strong shock the levels will be somewhat lower [19].



**FIGURE 6.** Intensity of 7.5-57 MeV protons at Voyager-1. Broad peaks in 1987 and 1998-99 are due to ACR hydrogen. Individual SEP events are difficult to observe after 1991.



**FIGURE 8.** Long-term average particle intensities measured at 1-AU (left panel, [21] and scaled to 75 AU (right panel). Pickup ion spectra are from Gloeckler [22]. The ACR and GCR measurements at 75 AU are from [19]. Note that above ~75 keV/nuc interstellar components dominate at 75 AU.



**FIGURE 7.** Solar-minimum proton spectrum at Voyager-1 compared to model and termination shock spectra [19].

### Comparative Particle Intensities

A comparison of long-term average spectra for oxygen nuclei at 1 and 75 AU is shown in Figure 8. Most of the 1-AU spectra were measured by ACE from 10/97 to 6/00 [21]. Inner-source and interstellar pickup ions are also shown [22]. The solar wind and SEP spectra were scaled to 75 AU using simple  $1/r^2$  scaling, although results in Figure 5 suggest a steeper radial gradient for energetic particles. Note that all components of solar origin, including inner-source pickup ions, have greatly decreased in importance at 75 AU, while those of interstellar origin (ACRs, GCRs, and interstellar pickup ions) have all increased in importance.



## SUMMARY

The examples shown here illustrate that while the Sun is still in control at 75 AU, it cannot exert this control on a day-to-day basis. Solar variations take six months or more to reach 75 AU, and in doing so most of the short-term variations become entrained in broad, long-lived structures. At this distance SEP intensities are attenuated by a factor of  $>10^4$  and anomalous and galactic cosmic rays are the dominant high-energy particle radiation. While the Sun still modulates cosmic rays on time scales that range from weeks to the 22-year solar cycle, the range of these variations is much smaller than at 1 AU, and it is evident that the nearby boundaries of the heliosphere exert a powerful influence on the environment.

**Postscript:** We now return briefly to the Kuiper Belt Society, who, having analyzed the data from the Voyagers, ACE, and SOHO, was debating the future direction of their space program. There were those that favored a sample return mission to Pluto, since it was hypothesized to have been the cradle of life in the solar system as it was carried into solar system on interstellar grains. However, in this planetary program lost out to a two-part space weather program. It was clear to KBO space physicists that the most important space weather threat at 75 AU was neither solar wind transients nor solar particles - rather it was the much higher radiation environment of the termination shock and ISM beyond, and the long-term stability of the shield provided by the heliosphere. Worried that if the “day the solar wind almost disappeared” ever lasted for a year or more, the heliosphere would suddenly shrink, placing their KBO in the ISM, they advocated sending a probe close to the Sun to study how the solar wind is accelerated. In addition, they realized that the heliosphere would also be compressed in size if it encountered a moderate-density interstellar cloud [23], and therefore advocated sending a probe upstream of the heliopause to explore the environment at the boundaries of the heliosphere and beyond, and to monitor approaching density enhancements in the local ISM. Of course, they called this two-part space-weather program “Living with the Stars”.

## ACKNOWLEDGMENTS

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